Argonne National Laboratory

A PULSED ELECTROMAGNETIC TEST SYSTEM
APPLIED TO THE INSPECTION OF
THIN-WALLED TUBING

by

C. J. Renken

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I. INTRODUCTION

Electromagnetic test systems based on the use of pulsed fields have been under development for a number of years, but pulsed systems sufficiently far enough advanced to be useful for actual nondestructive tests, or that offer potential advantages over conventional sinusoidal eddy-current test equipment are a relatively recent development. The most active test problem in the nuclear field to which electromagnetic test methods can be applied at present seems to be the inspection of small-diameter, thin-walled tubing which is usually used for fuel-element jackets, instrument-lead protection, or heat-exchanger applications. Such material is generally nonferromagnetic and is often limited to wall thicknesses below 1.25 mm by the requirements of heat transfer through the tube wall. Quality requirements for tubing intended for these applications are very strict, and some type of nondestructive test is generally valuable or even absolutely essential.

There is a considerable range of tube wall thicknesses over which both electromagnetic and ultrasonic methods are applicable; the ultrasonic method in general offers higher practical sensitivity, and the electromagnetic method greater convenience and the possibility of much higher speeds of inspection. It has been the practice at Argonne to inspect nonferromagnetic tubes of diameters over 5.8 mm and walls over 0.64 mm with ultrasonic methods and to inspect the rest with electromagnetic methods. The inspection of tubes below 5.8 mm by ultrasonic methods is plagued by formidable alignment problems; on the other hand, it becomes difficult to maintain a defect sensitivity of 10% of the wall thickness by electromagnetic tests on tubes with over 0.64-mm wall thickness. There is a no-man's-land of small-diameter heavy-walled tubes (for example, 3.8-mm ID x 0.64-mm wall) which is challenging for either method. In certain cases, also, noise in the tube caused by nondeleterious dimensional or metallurgical variables may produce a clear advantage of one method over another.

The object of the development effort culminating in this report was to explore the possible application of pulsed fields to electromagnetic testing and to produce test systems which would exploit some of the advantages of pulsed field operation if such advantages existed.

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II. RESTRICTION OF INDUCTION FIELDS TO
SMALL CROSS-SECTIONAL AREAS

The employment of pulsed fields made possible the development of devices called mask-aperture assemblies.[1] These are essentially devices for restricting the induction field established around a current-carrying coil to a small cross-sectional area so that the field at the region of restriction sets up in the test specimen a system of currents that is concentrated in a relatively small area. It is anticipated that any abnormality of a certain size in the specimen will produce a greater perturbation in such a limited field than it would in a more extensive current field. Other things being equal, this should result in higher ultimate sensitivity of the test system.

The idea of restricting the field size is, of course, not new, since many experimenters have employed ferrite cup cores, and also successively smaller test probes to try to improve the resolution and sensitivity of a test system. However, effective test probes can be reduced in size only to the point where the impedance changes produced in them by the defects in the test specimen do not become too small and so buried in drift that they cannot be satisfactorily extracted by the instrumentation. When pulses are used, however, it becomes practical to restrict the field in ways which are inherently extremely "lossy" since high peak-field strengths can be easily generated.

III. MASK-APERTURE ASSEMBLIES

One type of mask-aperture assembly, which is comparable in function to a point-type probe, has been described in an earlier report.[1] Another type has been developed that is similar in function to an encircling coil. A cross section of this device is shown in Figure 1. The aperture is formed by the narrow slit in the center. The field-generating coil is wound on the tapered opening leading to this slit and establishes an axial field in the region around the aperture. The pickup coil is wound coaxial with the field coil and channel for the tube. When a pulse of current of about 1-μsec duration is supplied to the field coil, pulses such as are shown in Figure 2 result, plotted with tube conductivity as the parameter. With a peak current in the field coil of about 10 Amp, the voltage has a peak amplitude of about 4 V, and no bridge or balancing arrangement of any kind is necessary to produce changes of the magnitudes of those shown in Figure 2.

The device is usually constructed symmetrically, that is, an identical pickup coil is mounted on the side of the mask shown as solid copper in Figure 1. When only tubing defects are of interest, subtracting the outputs of the pickups, one from another, provides an easy way of suppressing some types of dimensional interference in tubing.

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A. The Design of Point-type Mask-Aperture Assemblies

The optimum design of this equipment has been handicapped in the start by the difficulty of exact analysis. Measurements, analysis of arrangements of coils and conductors as computed, and above all intuitive experience of changes imposed upon each other—these outstrip any faltering steps toward quantitative analysis. The point-type mask-aperture assembly is chronologically the earliest development. A later version of one of these devices, which is adaptable to tube lengths of 1 to 3 μsec. is shown in Figure 1. It cannot be categorically stated that this is an optimum design or even a good design, but it does work better than others which have been tried.

Figure 1. A Coaxial Mask-Aperture Assembly
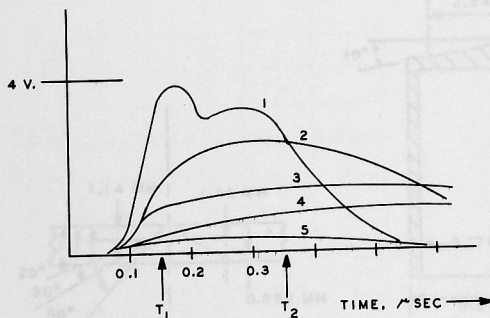
Figure 2

A Copy of Oscillograms Obtained from the Pickup Coil of a Coaxial Mask-Aperture Assembly

1. MASK EMPTY.
2. 304 STAINLESS STEEL TUBE, 4.42 MM OD X 0.254 MM WALL.
3. 304 STAINLESS STEEL TUBE, 4.42 MM OD X 0.229 MM WALL; 0.025 MM TUNGSTEN COATING ON INNER SURFACE.
4. 304 STAINLESS STEEL TUBE, 4.42 MM OD X 0.229 MM WALL; 0.051 MM TUNGSTEN COATING ON INNER SURFACE.
5. COPPER TUBE, 4.42 MM OD X 0.229 MM WALL.

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Figure 3. Line Drawing of a Mask-Aperture Assembly

The aperture shown is again a compromise. An aperture with a very acute included angle, of which a cylindrical hole is the limiting case,

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TUBE UNDER INSPECTION

PICKUP

COPPER MASK

APERTURE NO. 56 DRILL

2.54 CM

3.17 MM

10°

FIELD COIL 115 MMF

3.81 CM

3.17 MM

3.81 CM

CROSS SECTION OF THE MASK

1.14 DN

0.835 MM
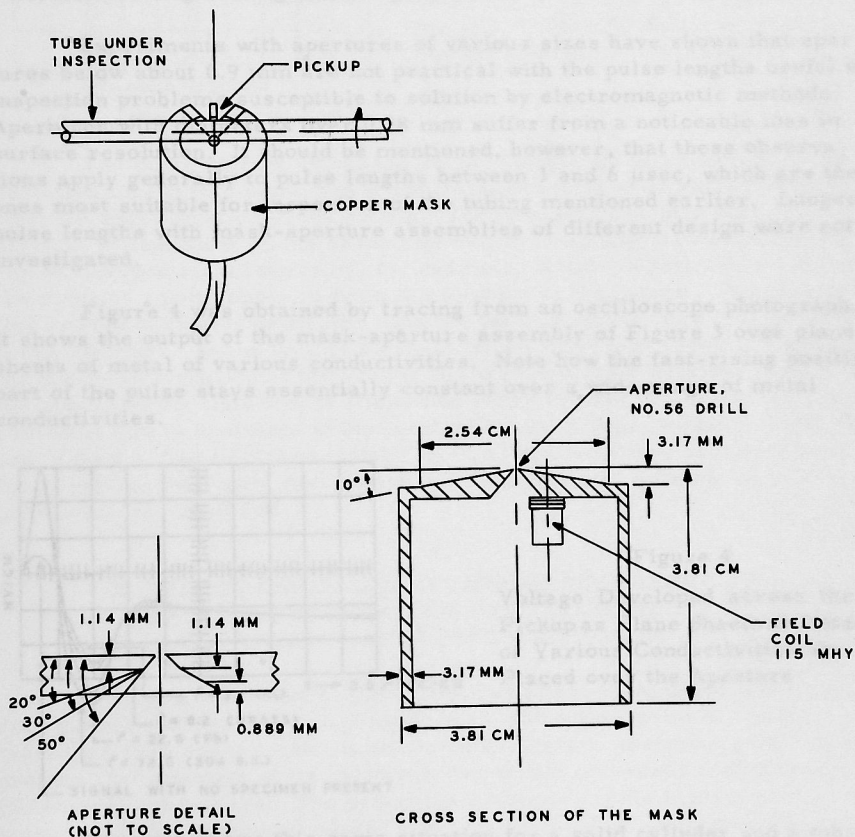
20°

30°

50°

APERTURE DETAIL (NOT TO SCALE)

Figure 3. Line Drawing of a Mask-Aperture Assembly

The aperture shown is again a compromise. An aperture with a very acute included angle, of which a cylindrical hole is the limiting case,

will allow practically no flux to emerge, whereas an aperture with too shallow an included angle will allow the passage of a field of expanded cross-sectional area, particularly of the low-frequency pulse components, and so reduces the surface resolution available from the device. The field coil must be located off the axis of symmetry of the aperture if there is to be a useful field established through it.

Longer pulses require heavier mask walls. The mask-aperture assembly shown will provide a signal of approximately 2 mV when near a good conductor and of 0.2 mV with no test specimen present when driven with a pulse of 2-Amp peak and 1.5-μsec duration. With repetition rates of about 1 kc, field coiling heating is not significant.

Experiments with apertures of various sizes have shown that apertures below about 0.9 mm are not practical with the pulse lengths useful in inspection problems susceptible to solution by electromagnetic methods. Apertures with diameters over 0.18 mm suffer from a noticeable loss in surface resolution. It should be mentioned, however, that these observations apply generally to pulse lengths between 1 and 6 μsec, which are the ones most suitable for inspection of the tubing mentioned earlier. Longer pulse lengths with mask-aperture assemblies of different design were not investigated.

Figure 4 was obtained by tracing from an oscilloscope photograph. It shows the output of the mask-aperture assembly of Figure 3 over plane sheets of metal of various conductivities. Note how the fast-rising positive part of the pulse stays essentially constant over a wide range of metal conductivities.

MV/CM

ρ = 3.2 (AL)
ρ = 8.2 (BRASS)
ρ = 22.6 (Pb)
ρ = 72.5 (304 S.S.)
SIGNAL WITH NO SPECIMEN PRESENT

T → 0.5 μ SEC/CM

Figure 4

Voltage Developed across the Pickup as Plane Sheets of Metal of Various Conductivities are Placed over the Aperture

Figure 5 shows this same situation for a solid cylinder and a tube of the same diameter and material. Figure 5 strongly suggests that if an inspection of tubing of this size were undertaken, a sampling pulse stationed at a point in time early in the pulse duration would provide information concerning tube-to-aperture spacing largely independent of tube wall

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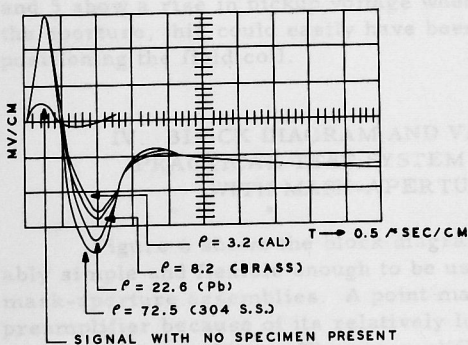

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thickness and the condition of the inner surface of the tube. The isolation of the information makes possible the electronic suppression of the troublesome "lift off" effect. The apparent delay of information returning from deep inside the tube wall is apparent also in Figure 2, but is much more pronounced in Figure 5 because of the much heavier tube wall.
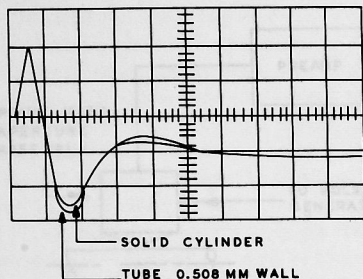

SOLID CYLINDER

TUBE 0.508 MM WALL

Figure 5

Voltage Developed across the Pickup as a 9.53-mm-diameter Cylinder of 304 SS and a Tube of the Same Diameter and 0.508-mm Wall are Placed over the Aperture. 0.5 μsec/cm.

The pulse voltage developed across the pickup is a function of the resultant flux at that point, and it can be varied over wide values depending upon the exact location of the pickup. The resultant flux at a particular location is dependent on the shape and wall thickness of the assembly, and can be changed significantly by, for example, drilling a hole in the side of the mask at a point opposite from the location of the pickup. The resultant flux is also obviously dependent upon the location of the field coil relative to the aperture. In the type of mask-aperture assembly shown in Figure 3, the pickup is stationed at the apex of the included angle near the surface of the mask and the field coil is positioned experimentally to obtain whatever resultant flux is desirable at the location of the pickup. Although Figures 4 and 5 show a rise in pickup voltage when a good conductor is placed over the aperture, this could easily have been changed into a decrease by repositioning the field coil.

IV. BLOCK DIAGRAM AND VARIOUS FEATURES OF A PRACTICAL TEST SYSTEM USED IN CONNECTION WITH MASK-APERTURE ASSEMBLIES

Figure 6 shows the block diagram of a test system which is reasonably simple and flexible enough to be used with either point or coaxial mask-aperture assemblies. A point mask-aperture assembly requires a preamplifier because of its relatively low output compared with that from the coaxial assemblies. The preamplifier has taken the form of a two-stage amplifier of approximately 1-Mc bandwidth built around low-noise pnp transistors. These amplifiers have a low-enough noise figure in this frequency range to reduce amplifier noise from these transistors to below the noise contributed by unidentified specimen variables in all test applications encountered to date. The block diagram includes an adder to be used

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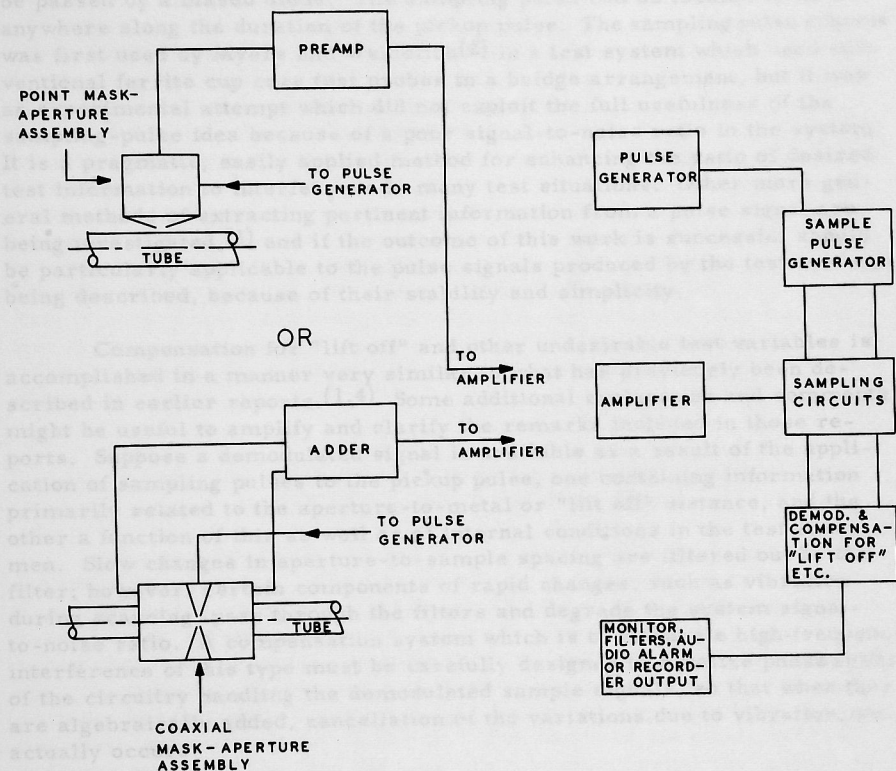

Figure 6. A Block Diagram of a Tube-inspection System for Operation with Either a Point-type or Coaxial Mask-Aperture Assembly

The pulse is usually generated by a thyratron discharging a capacitor through the field coil. No attempt has been made to shape the pulse, although this remains an interesting possibility. This circuit should be heavily damped, however, to reduce ringing of the field coil. Hydrogen thyratrons, such as the type 6130, seem very well adapted to this application, and provide high stability and long life. Test systems have been built with only solid-state devices; in this case the pulses were generated by a type 2N688 silicon-controlled rectifier. The number of turns and wire

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size on the field coil depend upon driving point impedance looking back into the generator, and the object is to obtain the highest peak magnetic intensity possible with whatever type of pulse generator and pulse are chosen.

The sampling can be accomplished by means of a short sampling pulse which elevates the section of waveform chosen to a value which will be passed by a biased diode. The sampling pulse can be located in time anywhere along the duration of the pickup pulse. The sampling pulse scheme was first used by Myers and Waidelich[2] in a test system which used conventional ferrite cup core test probes in a bridge arrangement, but it was an experimental attempt which did not exploit the full usefulness of the sampling-pulse idea because of a poor signal-to-noise ratio in the system. It is a pragmatic, easily applied method for enhancing the ratio of desired test information to interference in many test situations. Other more general methods of extracting pertinent information from a pulse signal are being investigated,[3] and if the outcome of this work is successful should be particularly applicable to the pulse signals produced by the test systems being described, because of their stability and simplicity.

Compensation for "lift off" and other undesirable test variables is accomplished in a manner very similar to what has previously been described in earlier reports.[1,4] Some additional explanation and comments might be useful to amplify and clarify the remarks included in those reports. Suppose a demodulated signal is available as a result of the application of sampling pulses to the pickup pulse, one containing information primarily related to the aperture-to-metal or "lift off" distance, and the other a function of this as well as of internal conditions in the test specimen. Slow changes in aperture-to-sample spacing are filtered out by the filter; however, certain components of rapid changes, such as vibration during scanning, pass through the filters and degrade the system signal-to-noise ratio. A compensation system which is to eliminate high-frequency interference of this type must be carefully designed to equalize phase shifts of the circuitry handling the demodulated sample signals, so that when they are algebraically added, cancellation of the variations due to vibration, etc., actually occurs.

Assuming this has been done, there is still one effect of spacing which must be accounted for, and this is the effect of the variation of aperture-to-metal spacing on system sensitivity. This condition can be corrected by application of the demodulated sample pulse signal associated with spacing changes to control the gain of an amplifier stage in the filter section. This forms a type of automatic gain control, but the mechanical conveying system must hold the variations in aperture-to-metal spacing large enough to have a significant effect on system sensitivity to frequencies low compared with the center of the filter passband, and to amplitudes which do not require more sensitivity than the system signal-to-noise ratio
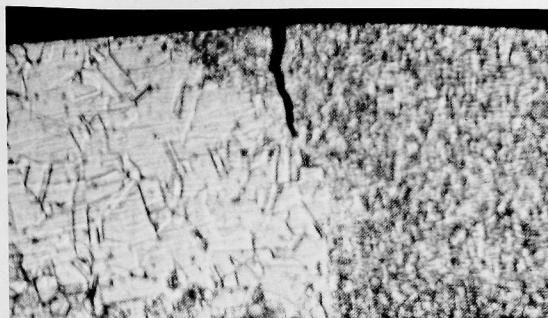
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A pulsed test system will not permit as high an inspection speed as a sinusoidal system because of the short-duty cycle inherent in the idea of pulse operation. As the repetition rate is increased, the maximum allowable inspection speed increases, but, of course, the system then is actually approaching a continuous wave system itself. The test system described in this report uses a repetition rate in the range from 1 to 2 kc, which permits linear inspection speeds of up to 6 m/min. This is more than adequate for most applications in the nuclear field in which a coaxial mask-aperture assembly can be used. But for larger tubes, for which a point-type mask-aperture assembly is needed for adequate resolution, 6 m/min is sometimes inconveniently slow. For example, for a tube of 12.7-mm dia, the rotational speed would be about 230 rpm. If the pitch is chosen as 0.76 mm/rev, the translational velocity along the tube axis will be about 17.8 cm/min. This is exceedingly slow compared with some commercial eddy-current test systems which test tubing at 35 m/min. But these systems are not required to test to the reject levels required in the testing of tubing for nuclear applications.

V. EXAMPLES OF TUBING INSPECTION UNDERTAKEN WITH
THE PULSED-FIELD TEST SYSTEM

Two examples will be cited of the application of these systems to the inspection of tubing. The first involved the inspection of low-carbon Type 304 welded stainless steel tubing of 4.04-mm ID x 0.229-mm wall. A coaxial mask-aperture assembly such as is shown in Figure 1 was used, except that this particular assembly was equipped with symmetrical pickups. No sampling pulses were employed owing to the relatively poor conductivity and thin wall of this material. Pulses of nominally 1.2-μsec duration were generated in the field coil. The center of the monitor-filter bandpass was at 13 cps, and the tube was conveyed through the coaxial mask-aperture assembly at 3.66 m/min. This particular tubing was afflicted with longitudinal cracks on the weld interface, generally less than 0.18 mm long and of varying depths; some of these are shown in Figure 7.

The second example relates to the inspection of Zircaloy-2 tubing of 10.66-mm OD x 0.686-mm wall. A mask-aperture assembly like that shown in Figure 3 was used to obtain adequate resolution in tubes this large. The usual procedure with point-type mask-aperture assemblies is to scan the surface spirally, but in this case the scanning was parallel to the longitudinal axis with the tube being turned 20° each pass until the entire surface had been covered. This tubing contained localized concentrations of hydrides strung out along the axis, and these produced serious

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37713   Oxalic Acid Etch   250X
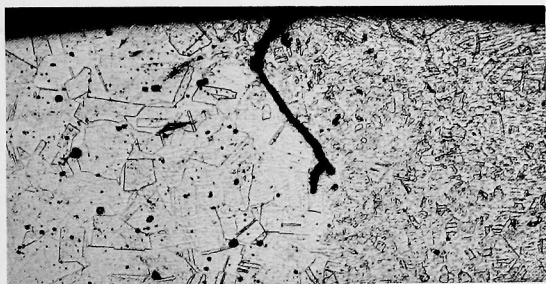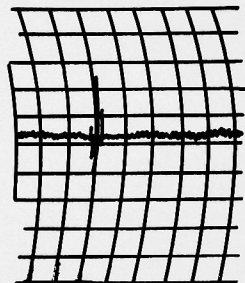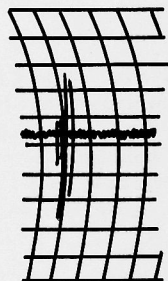
37722   Oxalic Acid Etch   250X

Figure 7. Cracks in Welded 304 Stainless Steel Tubing and Oscillograph Recordings of the Signals Produced by these Defects. Each crack was approximately 1.52 mm in length. The cracks are shown at their greatest depth. The recordings marked 20, 10, and 3 show the signals produced by 0.508-, 0.249-, and 0.071-mm-diameter drilled holes in this material.

interference when scanned transversely. The interference was minimized by longitudinal scanning. Whether or not this condition should be disregarded is a valid question, but outside the scope of this report. Longitudinal scanning speed was 4.88 m/min, with the center of the monitor-filter pass-band at 15 cps. Sampling pulses were used to increase sensitivity to ID defects. The pulse developed across the pickup looked very much like that shown in Figure 5. One pulse was stationed approximately 0.15 μsec from the beginning of the pulse to monitor changes in aperture-to-metal spacing. Figure 8 shows the response of the test system to various types of defects, and illustrates the effect of the time location of the second sampling pulse. The response to surface defects is very much reduced if both sampling pulses are in operation. Any test system with a differential or filtered output is subject to inquiry as to what happens when a long shallow defect is encountered but this question has been well covered in the literature[5] and will not be discussed here.

VI. CONCLUSIONS

The pulsed electromagnetic test systems discussed in this report seem to compare favorably with the commercial sinusoidal test equipment that is intended for parallel applications and with which the author is acquainted, and do offer some interesting advantages as a result of pulsed operation, notably stability and resolution. It is also most likely that further improvement in system performance will be realized as operating experience is acquired on a variety of test problems.
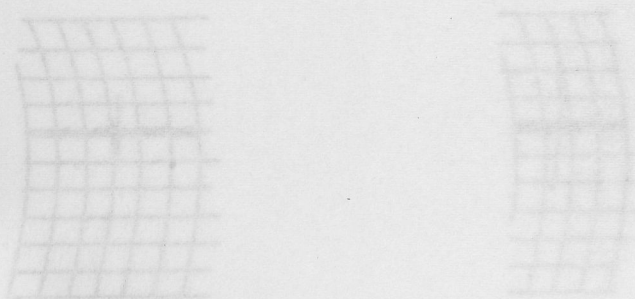
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by longitudinal scanning. Whether or not this condition should be disre-
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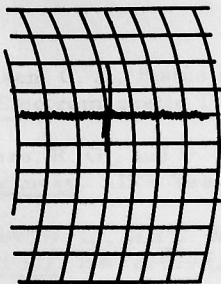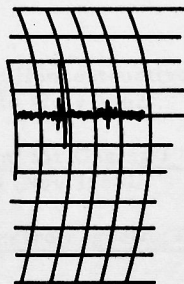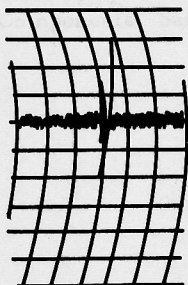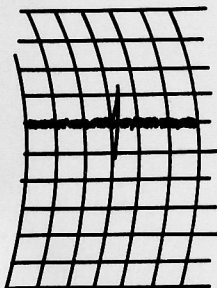experience is acquired on a variety of test problems.

Transverse electromachined notch,
3.1 mm long, 0.076 mm deep and
0.076 mm wide. t = 1.06 μsec.

Longitudinal electromachined notch,
3.1 mm long, 0.076 mm deep and
0.076 mm wide. t = 1.06 μsec.

Drilled holes, 0.076 mm and 0.152 mm
diameter respectively. t = 1.06 μsec.

ID crack, 0.127 mm deep by 1.5 mm
long. t = 1.06 μsec.

ID crack, 0.127 mm deep by 1.5 mm
long. t = 1.55 μsec.

Figure 8. The Response of the Inspection System to Various
Artificial and Natural Defects. The time position
of the second sampling pulse is denoted by t.

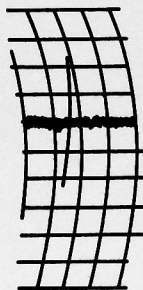Transverse electromachined notch, 3.1 mm long, 0.076 mm deep and 0.076 mm wide, $t = 1.08$ μsec.

Longitudinal electromachined notch, 3.1 mm long, 0.076 mm deep and 0.076 mm wide, $t = 1.08$ μsec.

Drilled holes, 0.076 mm and 0.165 mm diameter respectively, $t = 1.08$ μsec.

ID crack, 0.127 mm deep by 1.5 mm long, $t = 1.08$ μsec.

ID crack, 0.127 mm deep by 1.5 mm long, $t = 1.55$ μsec.

Figure 8. The Response of the Inspection System to Various Artificial and Natural Defects. The time position of the second sampling pulse is denoted by t.

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